Comparison of Organ Dosimetry for Astronaut Phantoms: Earth-Based vs. Microgravity-Based Anthropometry and Body Positioning

Presentation
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Purpose: To use NASA radiation transport codes to compare astronaut organ dose equivalents resulting from solar particle events (SPE), geomagnetically trapped protons, and free-space galactic cosmic rays (GCR) using phantom models representing Earth-based and microgravity-based anthropometry and positioning.
Methods: The University of Florida hybrid adult phantoms were scaled to represent male and female astronauts with 5th, 50th, and 95th percentile heights and weights as measured on Earth. Another set of scaled phantoms, incorporating microgravity-induced changes, such as spinal lengthening, leg volume loss, and the assumption of the neutral body position, was also created. A ray-tracer was created and used to generate body self-shielding distributions for dose points within a voxelized phantom under isotropic irradiation conditions, which closely approximates the free-space radiation environment. Simplified external shielding consisting of an aluminum spherical shell was used to consider the influence of a spacesuit or shielding of a hull. These distributions were combined with depth dose distributions generated from the NASA radiation transport codes BRYNTRN (SPE and trapped protons) and HZETRN (GCR) to yield dose equivalent. Many points were sampled per organ.
Results: The organ dose equivalent rates were on the order of 1.5-2.5 mSv per day for GCR (1977 solar minimum) and 0.4-0.8 mSv per day for trapped proton irradiation with shielding of 2 g cm^{-2} aluminum equivalent. The organ dose equivalents for SPE irradiation varied considerably, with the skin and eye lens having the highest organ dose equivalents and deep-seated organs, such as the bladder, liver, and stomach having the lowest.
Conclusions: The greatest differences between the Earth-based and microgravity-based phantoms are observed for smaller ray thicknesses, since the most drastic changes involved limb repositioning and not overall phantom size. Improved self-shielding models reduce the overall uncertainty in organ dosimetry for mission-risk projections and assessments for astronauts.

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Innovation/Impact: The purpose of this study is to evaluate the effects of incorporating microgravity-based anthropometry and body positioning on space radiation doses. Since NASA limits astronauts' occupational exposures to ionizing radiation based on risks to individual tissues and organs, improved accuracy of the modeled organ doses reduces the uncertain of mission risk projections and post-flight risk assessments. The results may have implications in proton and heavy ion therapy, since the space radiation environment consists largely of these species.

Introduction: NASA uses one-dimensional deterministic transport codes to compute doses for solar particle event (SPE), trapped proton, and galactic cosmic ray (GCR) components of the space radiation environment. In low-Earth orbit (LEO), trapped proton and GCR radiations are of concern, whereas outside of the Earth's magnetosphere, SPE can result in large organ dose equivalent and effective dose values. A previous study (1) investigated the differences between the phantoms currently employed by NASA and the University of Florida (UF) hybrid phantoms (combining the anatomic realism of voxel phantoms with the scalability of mathematical phantoms), which allow for greater flexibility in anatomical modeling and body positioning. While the previous study focused on differences in size and anatomical modeling, the present study focuses on differences in anthropometry and body positioning for Earth-based and microgravity-based phantoms.

Phantom scaling: Phantom scaling was first performed on the Earth-based anthropometry and body positioning. The phantoms currently used in NASA space radiation dosimetry are the Computerized Anatomical Man (CAM) and Computerized Anatomical Female (CAF) (2,3). These phantoms are in a standing position with arms at the side. The 50th percentile UF phantoms were created, and the 5th and 95th percentile phantoms were then created by scaling the 50th percentile phantoms; the body positioning mirrors that of CAM and CAF. The resulting Earth-based phantoms are shown in Figure 1.

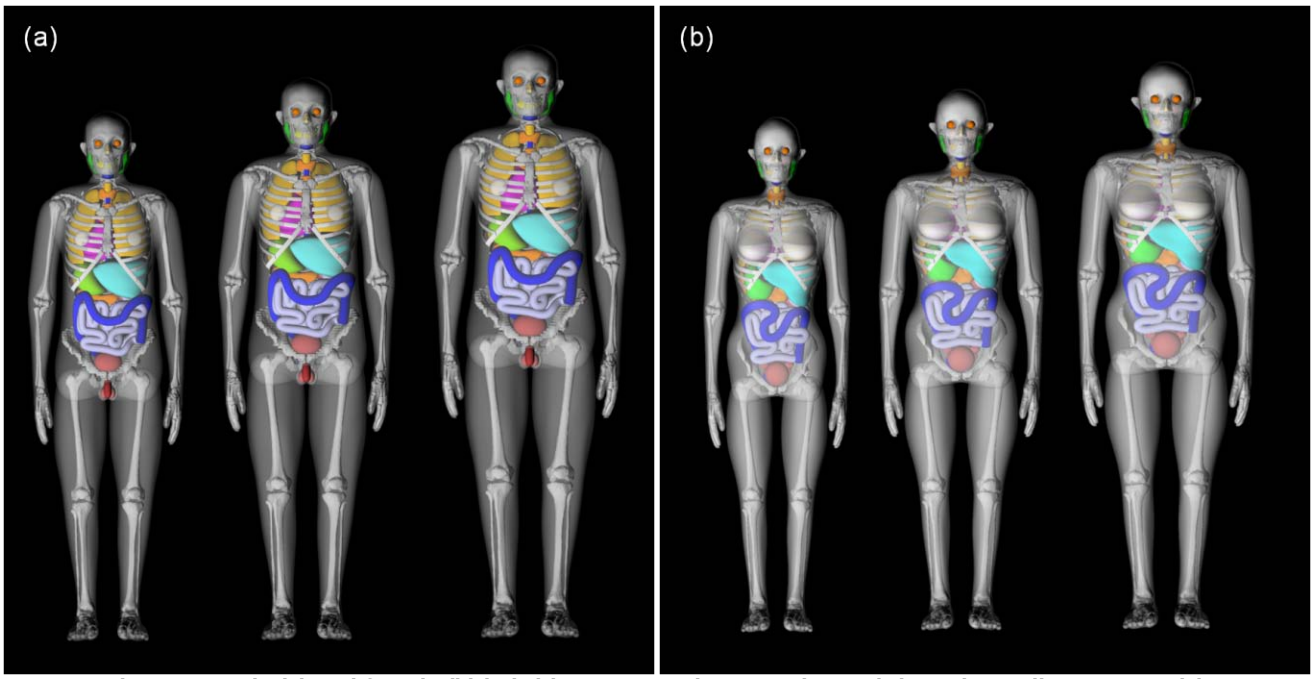

Figure 1. Male (a) and female (b) hybrid astronaut phantoms in Earth-based standing posture (1)

Next, it was necessary to construct the microgravity-based phantoms. This was performed on the 50th percentile phantoms by: lengthening the spinal column by 3%; repositioning the organs, head, ribs, arms, and legs accordingly; reducing the leg volume by 10% by decreasing thigh circumference; reducing the heart volume by 10%; reducing the bone density of trabecular bone by 10% for the spine, hips, and proximal femora; and finally positioning the arms and legs to reflect the neutral body position as defined in the NASA *Man-Systems Integration Standards* document (4). The 50th percentile male microgravity-based phantom is shown in Figure 2.

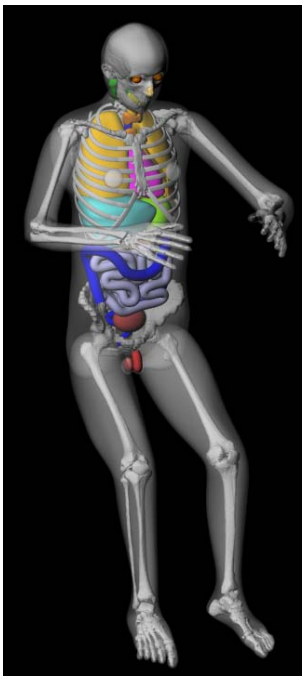

Figure 2. Male 50th percentile microgravity-based phantom

Dosimetry: Once the phantoms were scaled, they were voxelized and a layer of skin was added. A voxel-based ray tracer code was written to determine the amount of shielding between a point within the phantom and point on a sphere outside of the phantom. The body self-shielding distribution for each point was found by determining ray lengths, in water equivalent, for 512 rays emanating from each dose point, with each ray representing an approximately-equal fractional solid angle.

Once the body self-shielding ray lengths were determined, they were interpolated on depth dose distributions generated by BRYNTRN and HZETRN (NASA transport codes). The average dose equivalent over the 4π solid angle was found in order to represent free-space conditions, and the process was repeated for many dose points within each organ. It was then possible to determine the average organ dose equivalent by taking the average of the dose equivalent values for the dose points sampled within the organ. An example plot of the organ dose equivalents found for the Earth-based male phantoms irradiated under the August 1972 SPE (LaRC spectrum) with 10 g cm^{-2} aluminum equivalent (solar storm shelter) shielding is shown in Figure 3.

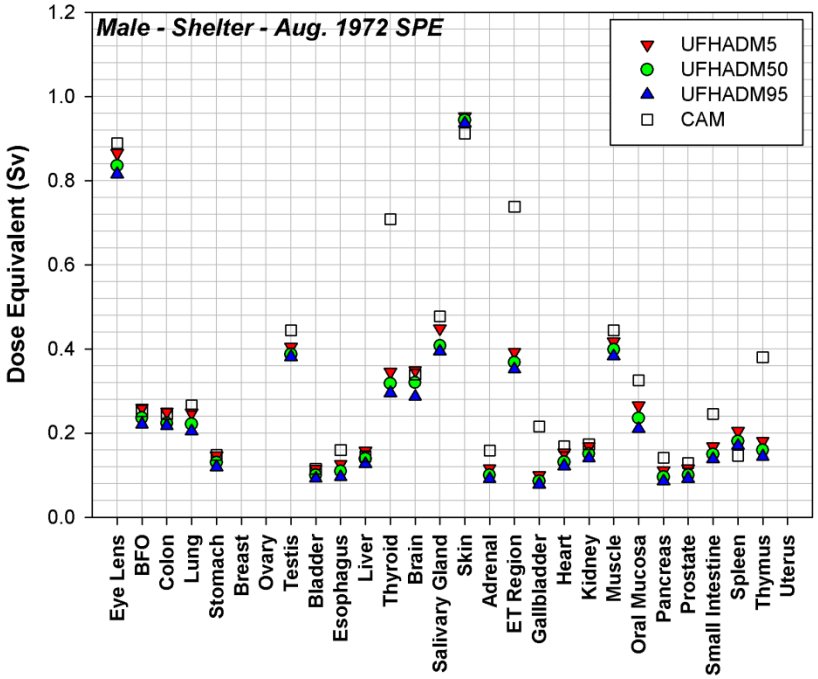

Figure 3. Organ dose equivalents for Earth-based male phantoms (August 1972 SPE, 10 g cm-2 aluminum equivalent shielding) (1)

Implications for space travel and therapy: As labeled, the example case shown in Figure 3 shows the influence of modeled phantom size in a standing posture on the evaluated organ doses. Male-female differences in the calculation of the risk of exposure induced death (REID) or cancer incidence (REIC) will be investigated in this and future work. The results of this research have implications for proton and other heavy ion therapy. One major issue with proton therapy is the possibility of motion causing differences between the intended dose distribution and the actual dose distribution. The situation is similar to the one experienced by astronauts being irradiated by an SPE, where organ doses are simulated under the assumption of a body position and orientation, which might not be accurate. In addition, GCR, which are comprised of a wide array of energetic ions ranging from protons to iron ions, are difficult to shield due, in part, to nuclear fragmentation. Heavy ion therapy also has challenges in terms of fragmentation; the ability to target tumors using the Bragg peak around radiosensitive structures makes it an attractive alternative to gamma therapy, but fragmentation unavoidably causes dose deposition in the structures that the treatment scheme is designed to avoid.

References

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